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Non-invasive recordings of fetal electrocardiogram during pregnancy using electric potential sensors

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In this letter, we report the early detection of fetal cardiac electrical activity recorded from the maternal abdomen non-invasively. We developed a portable and non-invasive, prototype based on electric potential sensing technology to monitor both: the mother and fetal heart activity during pregnancy. In this proof of principle demonstration, we show the suitability of our technology to monitor the fetal heart development starting at week twenty, when the fetus heart is approximately one-tenth the size of an adult's heart. The study was conducted for ten weeks to demonstrate how the maturation of the fetus leads to a change on the heart rate dynamics as it approaches birth. Importantly, electrocardiogram information is presented without any post processing given that our device eliminates the requirement of signal conditioning algorithms such as having to un-mix both, the maternal and fetal cardiac waveforms. The provided ECG trace allows extracting the heart rate and other heart activity parameters useful for further diagnostics. Finally, our device does not require any gels to be applied so movement induced potential is eliminated. This technology has the potential to be used for determining possible heart related congenital disorders during pregnancy. https://doi.org/10.1063/1.5042358

The field of electrocardiography started more than a century ago, since its invention in 1906 by M. Cremer.[1] Most of these advances were directed on measuring electrocardiogram (ECG) activity on adult patients given its optimal signal amplitude.[2]

During pregnancy, there are two main indicators to ensure the wellbeing of the fetus: the fetal motion inside the uterus experienced by the mother and the fetal heart rate (HR). The HR is a vital sign for clinicians, having an important role in assessing the need for medical interventions due to complications such as premature delivery or umbilical cord compression.[3]

The concept of fetal HR monitoring was introduced in the early 70's based on invasive methodologies consisting on intrauterine electrodes requiring the rupture of membranes. The low fetal signal-to-noise ratio especially in the presence of maternal ECG limited the wide spread of such technology. These advances did not contribute to the reduction of perinatal mortality,[4] and therefore have not yet reached a wide spread adoption. More than four decades later, there have not been any significant advances especially on the area of fetal ECG (fECG) monitoring technology.

Current non-invasive methods of monitoring fetal HR are limited to visualization using standard ultrasound techniques: Cardiotocography (CTG) is the most used method in medical practice, nevertheless, its sensitivity still requires to be improved.

The ultra-sonographic blood flow method evaluates the blood flow through arteries and veins in the fetus. However, it is not until week 20th when its ECG can be recorded, having HRs ranging from 110 to 180 beats-per-minute (BPM) during normal pregnancies.[5] This equipment is commercially available for maternity wards, however it is expensive, bulky and requires complex algorithms,

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for signal conditioning, still representing a challenge for both biomedical and signal processing communities.

Methods based on the use of silver-silver chloride (Ag-AgCl) transducing electrodes are commercially available HR monitors such as Meridian M110, Monica AN24 from Monica Health. These monitors are used in maternity wards as these require the skin to be in contact with gel (electrolyte) to generate a potential difference making electrodes not reusable. Here, the movement artefacts due to movement induced potential in surface electrodes can make these technologies inaccurate requiring the electrode to be repositioned.

Among these techniques fECG has proved to deliver faster and more reliably HR information compared with other methods.[6] In most of the countries, fECG test are only available at the hospital's maternity ward and mostly used during labor if required.

Women experiencing high-risk pregnancy factors such as high blood pressure, diabetes, preeclampsia and gestational high blood pressure require regular fECG monitoring to ensure the wellbeing of the baby. Although there are few home-based fECG products in the market, they are not suitable for daily/medical usage as their accuracy and portability needs to be improved.

In this paper, we present an electrometer based amplifier[7] prototype that has been developed using Electric potential sensing (EPS) technology for monitoring in utero fECG from the surface of the mother abdomen non-invasively.

We conduct a series of tests to measure fECG signals starting at week twenty of gestational age, when the fetus heart is approximately one-tenth the size of an adult heart.

The electrocardiogram information recorded during our experiments is presented without any post-processing techniques. This is because our EPS sensing device eliminates the requirement of signal conditioning algorithms such as un-mixing both, the maternal and fetal cardiac signals. The recorded fECG waveforms, presented in its raw form, contain the QRS complex characteristic present in any ECG trace. This allows the accurate HR extraction together with other heart activity parameters. Finally, our device does not require any gels to be applied so movement induced potential due to electrolyte solution is eliminated.[8–10]

The EPS sensor was invented and patented at the University of Sussex as a non-invasive sensing technology.[9] The EPS sensor is a feedback enhanced and stabilized electrometer-based amplifier that operates based on displacement current measurements.

The main technical characteristics of this technology have been published elsewhere.[7,11,12] Briefly, the sensor is designed with an external bias circuitry in a way that does not compromise the input impedance of the sensor. Its design includes associated feedback loops providing the functions of guarding, bootstrapping, and neutralization to enhance the input impedance, reduce the input capacitance, and maintain the electronic stability of the sensor.[12] The net effect of this combination and positive feedback techniques is to produce a broadband sensor (up to 100 MHz), with extremely high input impedance (up to 10^{18} Ω) and low effective input capacitance ($\sim 10^{-15}$ F) which is crucial for weak capacitive coupling with the patient. This arrangement results in a very low noise floor sensor at the operating frequencies of electrophysiological signals such as maternal and fetal ECG. Its performance as a non-perturbative detector for measuring fields or voltages with high sensitivity level has proven a maximum sensitivity of ~2.6 μV/m and an associated accuracy of 2%.[7]

Our previous work was focused on recording ECG and electroencephalogram (EEG) signals in adults using bespoke wired and wireless prototypes.[13,14] Our findings validate the safety and non-invasive use of our EPS technology for electrocardiography applications.

The main requirements for recording electrophysiological activity is the ability to clearly distinguish cardiac events produced by different sources independent of their amplitude and location, such as those produced by the fetus and the mother's heart. Here, the prototype design considers three requirements: first, the instrumentation should allow the electrical detection of low amplitude fetal signals with high signal-to-noise ratio considering the fact these will require to be recorded though different amniotic layers and tissues i.e. the maternal body surface.[7,15] Second, the composition of these structures will dynamically experience changes in electrical conductivity though gestation especially as the amniotic fluid, placenta and fetus increase their volume.[16] Third, the device should be capable of detecting both mother and fetus signals independently eliminating the requirement of complex post processing algorithms.

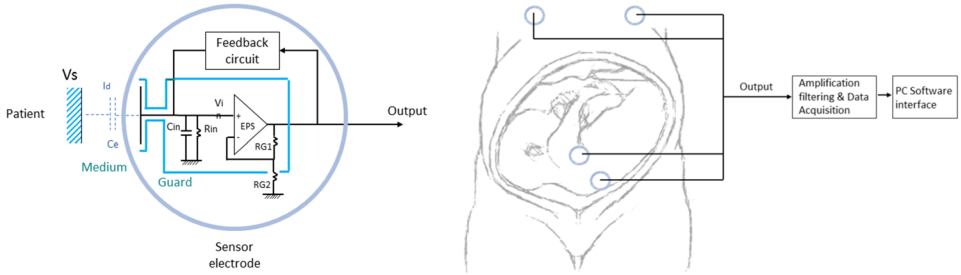

FIG. 1. Diagram depicting the electrodes main blocks (left) and electrodes placement for maternal and fetal ECG recordings (right).

The prototype described in this paper was built using a bespoke ultra-high input impedance EPS sensor with internal input bias current circuitry and guarding. The prototype was designed using four dry electrodes. The circuit design incorporates an electrometer and utilizes the electronic feedback techniques in order to increase the input impedance and maintain stability. The voltage output from the sensor is fed to an analogue filtering (0.5–100 Hz) and amplification stage. This customized version of the sensor has been used for recording maternal and fetal ECG signals reported in this work. The analogue output is fed to a commercial National Instruments data acquisition system (i.e., DAQ NI USB 6008 card). The data was acquired on a laptop computer. Display and storage of the data is controlled using a custom designed graphical interface based on LabVIEW software including an algorithm for peak detection to determine HR values. Figure 1 shows the experimental setup used.

The recording period started at week twenty of gestational age, when fetal ECG has enough amplitude to be recorded though maternal tissue. The fetal HR can be detected starting by the third week of gestational life, experiencing a considerable growth within the initial stages of pregnancy.[17]

For this proof of principle demonstration, a single participant with singleton pregnancy was evaluated lying at 15° right or left lateral position (depending on fetal presentation during the initial weeks). The participant gave written informed consent before participating in the study and after we explained the experiment protocol, as approved by the Science &Technology Cross-Schools Research Ethics Committee (C-REC) University of Sussex with application ID number SOP/RGO/ER241/02. All experiments were performed in accordance with relevant guidelines and regulations.

Our protocol was carried out for ten weeks, before the *vernix caseosa* layer is formed (i.e. around 28^{th} and 32 weeks), which almost electrically shields the fetus and makes recording very difficult due to its very poor conductivity ranging between $\sim 10^{-7}$ to 10^{-5} Ω^{-1} m^{-1} according to Ref. 15.

According to Ref. 2 there is no exact or even approximate optimal electrode positioning as this is likely dependent on the fetal location and presentation. For most of experiments, fECG recordings were carried out positioning the first electrode on top of the maternal abdomen approximately below the umbilicus as it is shown in Fig 1. The second electrode was positioned on the bottom of the maternal abdomen (above the bikini area). This was determined by identifying the fetal presentation by using a fetal HR monitor (Huntleigh Healthcare Fetal dopplex). For recording the maternal ECG, two electrodes were used and positioned on the mother's chest (see figure 1).

Recordings for each week were carried out in a private room and calm atmosphere to ensure recording stability. This was carried out for a period of up to 30 seconds and repeated 5 times.

Figure 2 shows a single ECG pulse (raw data) for both mother and the corresponding fetal ECG collected during gestational weeks 20, 25 and 30 respectively. Here, some similarities on the mother and fetus ECG traces are observed such as the QRS complex. The fECG amplitude is smaller compared with the mother's ECG. fECG amplitude changes as the gestation makes progress but it is also highly dependent on the electrode position and fetal presentation. Finally, one of the most considerable changes occurs in the T-wave, which is known to be very weak in fetuses and newborns.[2]

The low noise levels achieved within our sensor design avoid the use of post processing stages, which allows visualizing the QRS complex in the raw fetal ECG trace as it is shown in Fig 2.

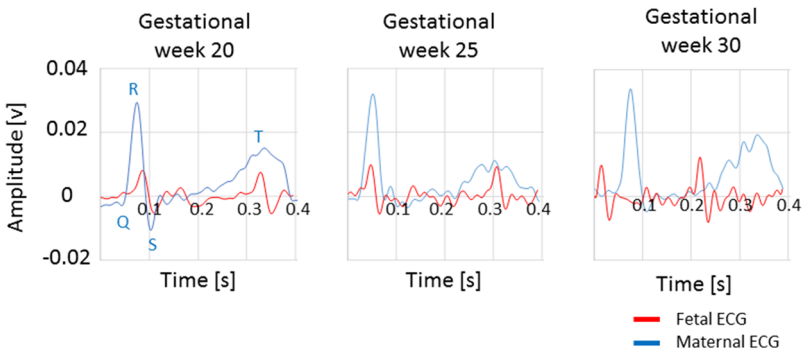

FIG. 2. Raw fetal and maternal ECG traces for gestational weeks 20, 25 and 30.

In previous work, we showed the detection of weak localized electrical fields coming from various samples such as electrical circuits, a single cell containing saline solution, and finger prints using EPS technology.[8–10] Our findings validated the feasibility of our technique to detect such small signals within the same medium, without these being mixed achieving spatial resolutions <230 μm.

In our case, both the mother's and the fetal ECG signals are not only spatially separated but have tissues in between representing a favorable scenario. Therefore our sensor design, is able to retrieve the unmixed cardiac information from both sources independently due to the spatial localization of both hearts (as shown in Fig 3). This eliminates the need of complex algorithms and computational power required for this task in contrast with results reported in literature.[18–22]

In figure 3, we show the first 10 seconds of the raw data acquired with our device. It shows the fetal and maternal ECG traces recorded during gestational week 23. This illustrates the feasibility of our device for continuous monitoring of both maternal and fetal ECG traces non-invasively. These recordings show ECG signals including information such as QRS complex and R-R interval, required to calculate HR values and HR variability with high accuracy. Such information is useful to clinically assess congenital cardiac diseases such as arrhythmia and Long-short QRS complex and to extract neuro cardiac information to gain understanding about processes associated with body auto regulation (i.e. blood pressure, heart vascular tone etc.).[23,24] The fetal HR was 165 bpm and the maternal HR was measured to be 75 bpm.

Finally, Figure 4 (left panel) shows the HR evolution versus time and the HR variability analysis (right panel) for both: the fetus and the mother measured though out the full recording period (starting from week 20 until week 30).

Through the recordings, we found that the maternal ECG remains steady having a mean basal HR of 67.3 ± 0.871 BPM. As it is expected in a healthy pregnancy,[4] the acquired fetus basal HR values show normal evolution starting with high HR values within the initial weeks of gestational age, reaching a maximum of 176 BPM. HR settled down as birth approached with values of 135 BPM, which is in accordance with related studies.

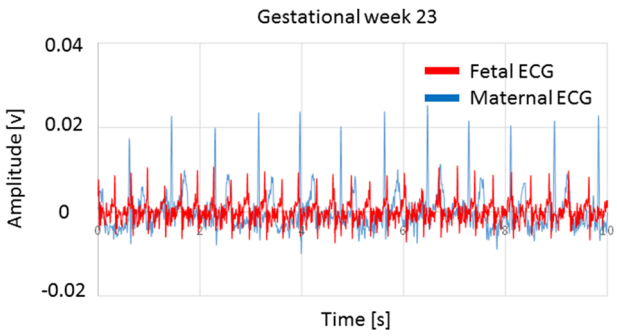

FIG. 3. Example of raw fetal and maternal ECG traces for gestational week 23.

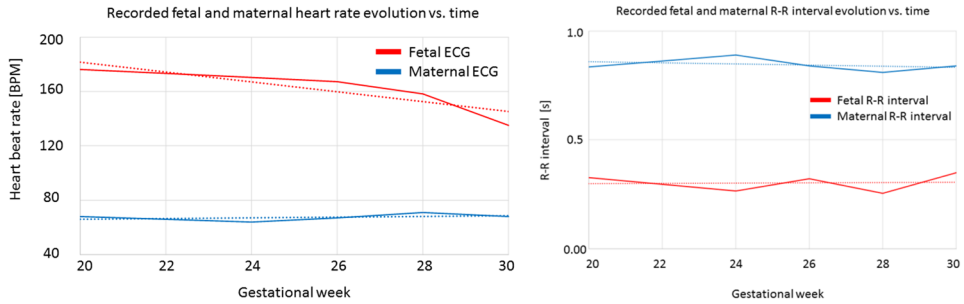

FIG. 4. Fetal and maternal heart rate evolution (left panel) and heart rate variability analysis as a function of time/gestational week (right panel).

In Figure 4 (right panel), the R-R interval evolution is plotted as a function of time for both the mother and the fetus. The mean maternal HRV found was 0.85± 0.010, which falls within the normal ranges reported in literature.[24–26] On the other hand, for the fetal R-R interval, we found a mean variation of 0.31± 0.014 s, which is in agreement with previous studies reported on Refs. 18, 27–30.

In summary, we developed and tested a prototype based on EPS technology to record both maternal and fetal ECG signals non-invasively starting at gestational week twenty. Through a series of experiments, we present results that confirm the temporal relationship between the fECG data collected using our device compared with those results presented in related works. The presented device offers multiple advantages such as its non-invasive nature; dry electrodes that do not require skin preparation or gels to be applied, reducing moving artifacts. It is capable of detecting the maternal and fetal ECG signals independently, therefore eliminating the need of using complex algorithms. The sensor's low noise levels provide accurate recordings of fECG signals directly from the raw data without requiring post-processing techniques. The designed device is portable due to its reduced footprint sized 40x100x100 mm and can be used as real time recording equipment.

We believe that these results open up the development pathways for future applications such as embedding the sensor within a wearable garment for high-risk pregnancies and outside the clinics given that the footprint can be further reduced and can be battery operated due to its low current consumption.

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